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Constraining the ^{12}C+^{12}C fusion cross section for astrophysics

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Abstract. ^{12}C+^{12}C is one of the single most important nuclear reactions in astrophysics. It strongly influences late evolution of massive stars as well as the dynamics of type Ia supernovae and x-ray superbursts. An accurate estimation of the cross section at relevant astrophysical energies is extremely important for modeling these systems. However, the situation is complicated by the unpredictable resonance structure observed at higher energies. Two recent studies at Notre Dame have produced results which help reduce the uncertainty associated with this reaction. The first uses correlations with the isotope fusion systems, ^{12}C+^{13}C and ^{13}C+^{13}C, to establish an upper limit on the resonance strengths in ^{12}C+^{12}C. The other focuses on the specific channel ^{12}C+^{12}C→^{23}Mg+n and its low-energy measurement and extrapolation which is relevant to s-process nucleosynthesis. The results from each provide important constraints for astrophysical models.

1 Introduction

The ^{12}C+^{12}C fusion reaction is critical to a number of astrophysical systems. Perhaps the most obvious is in late stellar evolution of massive stars (>8M$_{\odot}$), where the low-energy reaction cross section sets the thermodynamic conditions in the stellar core and surrounding shells during carbon burning. The carbon fusion reaction is also key for triggering type Ia supernovae [1], where the low-energy cross section affects the thermodynamic conditions within the white dwarf just prior to the explosion. The same is true for the x-ray superburst which is also triggered by the carbon fusion reaction [2, 3]. Superbursts are extraordinarily intense x-ray bursts (about 1000 times brighter and longer than normal x-ray bursts). Only a handful of observations exist, but the ^{12}C+^{12}C reaction cross section is critical for modeling these systems.

Measurement of the ^{12}C+^{12}C cross section at low energies is difficult. The fusion reaction proceeds through the formation of the ^{24}Mg compound nucleus at high excitation energy (∼15 MeV) followed by alpha, proton, or neutron decay to states in the corresponding residual nuclei (^{20}Ne, ^{23}Na, and ^{23}Mg respectively). The proton and alpha decay channels are the most probable due to their positive Q-values (Q_p=+2.2 MeV and Q_α=+4.6 MeV), while the neutron channel comprises less than 1% of the total yield at astrophysical energies [4] due to a negative Q-value (Q_n=-2.6 MeV).

The ^{12}C+^{12}C cross section falls off steeply at low energies due to the low probability for penetrating the Coulomb barrier. The important energy range for astrophysical applications is generally between 1-3 MeV in the center-of-mass system, at which the cross section is expected to be as low as 10^{-22}b using the extrapolation from Ref. [5]. This is prohibitively low for measurements with current ion source/accelerator technology. Therefore, the reaction cross section must be modeled at the lowest astrophysical energies. However, the modeling is complicated by the existence of resonances in the excitation function. This resonance structure was first observed in 1960 by Almqvist, Bromeley, and Kuehner [6, 7] and was attributed to molecular resonances in the ^{24}Mg compound nucleus. The resonances were observed below the barrier down to the lowest measured energy in all decay channels. To date, there is still no theory which can reliably predict the location of these resonances, nor is there sufficient experimental data which could be used to guide theoretical predictions. Much of the difficulty is related to the high level density in the excitation energy region where the states are populated in the ^{24}Mg compound nucleus. However, the ^{12}C+^{12}C reaction is very selective in the states that it can populate (only T=0 and even J$^+$ states), since the reactants are identical T=0 and 0$^+$ bosons. Thus far, it is not clear how to populate only these relevant states in ^{24}Mg via alternative reaction channels making it difficult to identify the states of interest in the appropriate energy range.

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The unpredictability of the $^{12}C+^{12}C$ resonance structure at low energies introduces a large degree of uncertainty in the astrophysical cross sections. Recent work at the Nuclear Science Lab (NSL) at Notre Dame (ND) has been focused on reducing this uncertainty through direct measurements and improved cross section extrapolation techniques. In this paper, two projects are highlighted. The first involves studying the carbon isotope fusion reactions ($^{12}C+^{13}C$ and $^{13}C+^{13}C$) to establish an upper limit on the $^{12}C+^{12}C$ cross section at all energies. The second project involves direct measurements of the neutron channel at astrophysical energies while using experimental results for the mirror proton channels to provide a reliable cross section extrapolation at lower energies.

2 The Isotope Fusion Project

In recent years, the $^{12}C+^{12}C$ low-energy cross section has become even more uncertain due to the observation of an extremely large resonance at 2.14 MeV by Spillane et al. [8]. This resonance was observed in both the proton and alpha channels based on detection of the gamma-decay of the first excited states in the residual nuclei. Though the resonance was very narrow compared to the ones at higher energies (<12 keV compared to ~100 keV), the S*-factor was seen to jump by a factor of 300 in the alpha-channel relative to the average baseline value (other resonances typically enhance the S-factor by less than a factor of 5). Nevertheless, the existence of such a strange resonance would open the possibility that more like it could exist at even lower energies, perhaps even larger.

This increased uncertainty was soon after exploited to reconcile superburst models with astrophysical observations. The driving issue was that the column depth of the explosion within the neutron star inferred from the observed light curves was inconsistent with models (see Ref. [3] and references therein). The superburst models were unable to generate sufficient heat to trigger the $^{12}C+^{12}C$ thermonuclear runaway at the suitable shallow depths. However, with a sufficiently large resonance in the fusion cross section, this problem could be solved. This was proposed by Cooper, Steiner, and Brown, who investigated the feasibility of a large resonance at 1.5 MeV [3]. The location and strength of the potential resonance was estimated based on the properties of the large resonance observed in the Spillane measurement. They argued that it was not unreasonable to expect that a strong enough resonance might exist that could explain the triggering of the superburst as the observed column depths without the need for some unknown heat source.

2.1 An upper limit on the resonance strengths

In an attempt to learn about the gross structure of the low-energy $^{12}C+^{12}C$ excitation function, the carbon isotope fusion reactions were recently studied at ND. The $^{12}C+^{13}C$ and $^{13}C+^{13}C$ cross sections were known to display much smoother behavior below the Coulomb barrier [9, 10]. The measurement of $^{12}C+^{13}C$ in Ref. [9] stops above 3 MeV

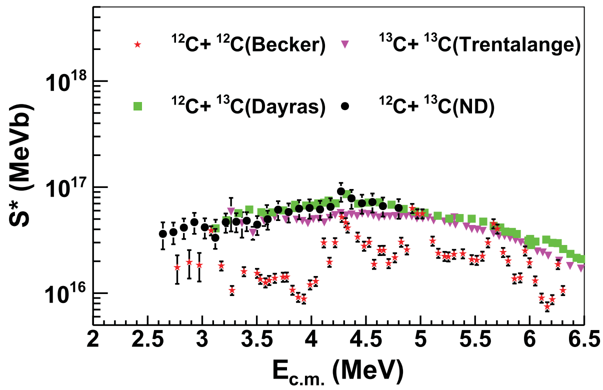

Figure 1. The S*-factors for the carbon isotope fusion reactions: $^{12}C+^{12}C$ from Ref. [14], $^{13}C+^{13}C$ from Ref. [10], $^{12}C+^{13}C$ from Ref. [9], and $^{12}C+^{13}C$ from ND [11].

(center-of-mass). The recent work at NSL was able to extend the measurements much further below the Coulomb barrier to 2.6 MeV (Fig. 1) where the cross section drops by a factor of 50. The details of the experiment can be found in Ref. [11]. The results show good agreement with the previous measurement from Ref. [9] in the overlapping energy range. However, the most striking result is seen by comparing the $^{12}C+^{13}C$ excitation function with those of $^{13}C+^{13}C$ and $^{12}C+^{12}C$ using the same cross section factor: $S^*(E) = \sigma(E)E\exp\left(\frac{87.21}{\sqrt{E}} + 0.46E\right)$ (Fig. 1). It is seen that $^{12}C+^{13}C$ and $^{13}C+^{13}C$ display the same general trend with good agreement within the systematic uncertainties. $^{12}C+^{12}C$, on the other hand, always falls below except at the resonance energies where good agreement is achieved. This correlation holds true across the entire measured energy range, except the unusually strong resonance reported by Spillane [8]. The reason for this has been explained as due to the relatively lower level density in the compound nucleus for $^{12}C+^{12}C$ compared to $^{12}C+^{13}C$ and $^{13}C+^{13}C$ [11, 12]. As a result, the isotope fusion systems provide an upper limit for the $^{12}C+^{12}C$ system. Since the isotope systems are much easier to model due to their smooth behavior, such an upper limit could be predicted down through the astrophysical energy range. To this end, a coupled-channels (CC) calculation was done by H. Esbensen [13]. By using nuclear structure data for ^{12}C and ^{13}C, the experimental point-proton density for ^{12}C, and tuning the CC parameters to the $^{13}C+^{13}C$ measurement from Ref. [10], Esbensen was able to provide a prediction for the $^{12}C+^{13}C$ system which displayed good agreement with experimental data down through the lowest measurements provided by ND, and more importantly, a prediction of an upper limit for the $^{12}C+^{12}C$ system which showed good agreement with the experimental resonant cross sections (Fig. 2).

The new upper limit is compared to the resonance proposed in Ref. [3] in Fig. 2. The hypothetical resonance at 1.5 MeV is seen to be about 40 times larger. Furthermore, the resonance observed by Spillane at 2.14 MeV is also found to be well above the newly predicted upper

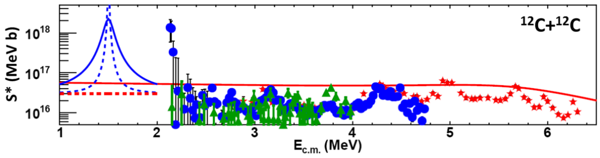

Figure 2. The total fusion S*-factors from Ref. [14] (red stars) and [8] (blue circles), along with the proton S*-factor from Ref. [15] (green triangles) are shown with the predicted upper limit (solid red) and hypothetical resonances from Ref. [3] (blue). The CF88 extrapolation [5] is also shown (dashed red).

limit. This suggests that if these resonances exist, they must be present due to some unknown phenomenon that is not present for the resonances observed at higher energies. A more likely explanation is that such large resonances in the $^{12}C+^{12}C$ system do not exist and the observation by Spillane was influenced by a beam-induced background reaction that was not taken into account [11, 15]. Indeed, a more recent low-energy measurement [15] was unable to confirm the existence of this resonance in the proton channel (Fig. 2). It would be extremely important to provide experimental confirmation or denial of this resonance which has already shown great implications for modeling astrophysical systems. However, such experiments remain extraordinarily challenging and require the use of large-current accelerators with ultra-clean targets under high vacuum, as well as efficient and selective detection systems.

3 The $^{12}C+^{12}C\rightarrow^{23}Mg+n$ project

The second half of this paper highlights the work done at ND to reduce the uncertainty in the neutron branch of the $^{12}C+^{12}C$ reaction. This has been done through a combination of direct measurements and an improvement in the low-energy extrapolation of the cross section. Multiple measurements were made at NSL which have been presented previously in Refs. [16–18]. Only the most recent results are presented here. More details can be found in Ref. [19].

3.1 Motivation

The primary impact of the $^{12}C+^{12}C\rightarrow^{23}Mg+n$ reaction (hereafter referred to as CCN) surrounds the component of s-process nucleosynthesis which occurs during convective shell-carbon burning of massive stars. The so-called weak s-process is responsible for the elements between iron and strontium and occurs also during convective core helium burning in massive stars with the neutrons coming mainly from the reaction $^{22}Ne(\alpha,n)^{25}Mg$ (see Ref. [20] and references therein). The (α,n) rate determines to what extent ^{22}Ne is consumed during helium burning. Any leftover ^{22}Ne is rapidly consumed during the hotter carbon burning stages. Despite a relatively low neutron branch, the carbon fusion reaction may contribute a significant flux of neutrons during these burning stages. This additional neutron flux can have an influence on heavy-element production, including abundances near s-process branching points and s-only isotopes below mass 100. Indeed, a sensitivity of the abundances on the CCN reaction has already been demonstrated in Ref. [21]. The range of enhancement factors investigated in that work reflects the large uncertainty in this reaction which up to now has not been quantified.

Prior to our work, the low-energy CCN cross section was measured only two times. The first measurement by Patterson et al. [22] failed to reach low enough energies for astrophysical relevance stopping at 4.23 MeV (energies are quoted in the center-of-mass frame unless otherwise noted). The important energy range depends on the temperature of the astrophysical environment, but for shell-carbon burning is generally between 2.8 and 3.8 MeV. A subsequent measurement by Dayras et al. [4] provided data down to 3.54 MeV. The cross section at lower energies was estimated using a statistical model calculation which was normalized to experimental data. Due to the resonance structure present in $^{12}C+^{12}C$, the CCN excitation function is observed to deviate from the statistical model calculation by as much as a factor of 4 [4]. As a result, the uncertainty in the estimation at lower energies, where resonance effects can be amplified, is quite large. Presumably this is the reason why Caughlan and Fowler decided to leave out the Dayras extrapolation from their 1988 evaluation of thermonuclear reaction rates (CF88) [5] estimating the CCN rate simply as a step function at T=1.7 GK. The implications of this have propagated through subsequent stellar models which have adopted this evaluation through the following two decades. A prime example of where this might be important is in the work by Limongi and Chieffi on the production of ^{60}Fe in massive stars [23]. ^{60}Fe is believed to be produced primarily during shell-carbon burning (the extent of this depends on stellar mass) which generally takes place at temperatures below 1.7 GK. Since ^{59}Fe is unstable with a relatively short half life ($t_{1/2}$=44 days), the high neutron flux during shell-carbon burning is necessary to bridge the instability gap to produce ^{60}Fe from stable ^{58}Fe. By ignoring the CCN reaction, the neutron flux and, therefore, ^{60}Fe production is likely underestimated. Since ^{60}Fe decay can be observed directly in the galaxy [24], it is important to provide accurate nuclear data wherever possible in order to answer key questions about stellar evolution. Additionally, the production of ^{26}Al in the galaxy, which is a similarly long-lived isotope produced in massive stars and observed by gamma-ray satellites, is expected to be sensitive to the CCN reaction [25]. These observations can provide further information on stellar structure and galactic chemical evolution provided reliable nuclear data is available. Therefore it is important to reduce and quantify the uncertainty in the CCN reaction as well as provide the most accurate cross section estimation possible.

3.2 Experiment

The early measurements of CCN were done by detecting the residual ^{23}Mg which β-decays with a half life of 11.3

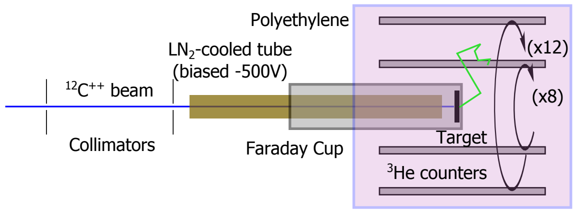

Figure 3. The setup for the CCN cross section measurement.

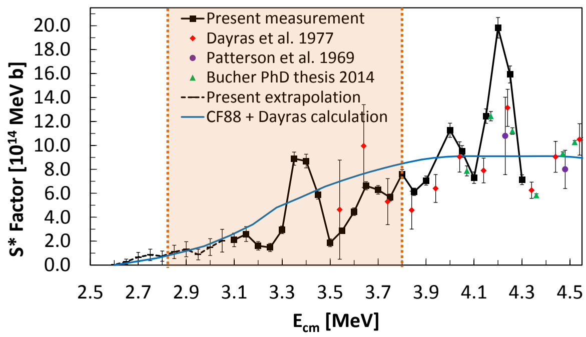

Figure 4. The present CCN S*-factor results are shown with the previous measurements from Refs. [4, 19, 22]. Also shown is the Dayras extrapolation and the new extrapolation from this work (Sect. 3.3). The astrophysical energy range is shaded orange.

seconds. Similar measurements were recently performed at NSL and have been highlighted in Refs. [16–19]. This paper will summarize only the most recent measurement at NSL which detected the neutrons produced by CCN. In this experiment, a ^{12}C beam was produced by a cesium sputter ion source and injected into a 11 MV FN tandem Van de Graaff accelerator. Beam energies between 8.7 and 5.1 MeV were studied. The beam impinged on a 1mm-thick highly-ordered pyrolytic graphite (HOPG) target which is known to be relatively free of hydrogen contamination [15]. The target was positioned inside a Faraday cup while -500V suppression voltage was applied by a long copper tube cooled with liquid nitrogen positioned just upstream. A schematic of the setup is shown in Fig. 3. The target was surrounded by 20 ^{3}He proportional counters embedded in a block of polyethylene. The ^{3}He counters were arranged in two concentric rings with 8 in the inner ring and 12 in the outer ring. The neutron detection efficiency was obtained from a Geant4 simulation package which was calibrated by experimental efficiency data [26] but modified for neutron kinematics characteristic of ^{12}C+^{12}C [19].

The main background source in the total neutron yield was due to ^{12}C+^{13}C$\rightarrow$^{24}Mg+n where ^{13}C was naturally present in the target at 1.1%. To measure the neutron yield from this reaction, a ^{13}C beam was used, and the yield curve was measured across the same energy range in the center-of-mass. The resulting yield curve was used to subtract the ^{12}C+^{13}C background from the total neutron yield (see Ref. [19] for details) leaving the yield from CCN.

The resulting S*-factor from the thick target yield is shown in Fig. 4 along with the previous measurements, including the earlier results from NSL. It is seen that the new results extend deep into the astrophysical energy range and display good agreement with the earlier measurements at overlapping energies. For comparison, the Dayras extrapolation is plotted with the data. The new results appear to follow the extrapolation well despite an obvious resonance structure which seems to be dampening as the reaction threshold at 2.6 MeV is approached. The new results greatly reduce the stellar rate uncertainty since the energy range requiring an extrapolation has been significantly shortened.

3.3 Extrapolation

The Dayras extrapolation shown in Fig. 4 is computed by applying the statistical model calculation of the neutron branching ratio from Ref. [4] to the CF88 estimation of the ^{12}C+^{12}C total fusion cross section [5]. Although this extrapolation continues to provide a reasonable approximation of the measured cross section, the uncertainty remains to be addressed which arises primarily from the unknown resonant structure in the unmeasured energy range. To better account for the resonance structure in the extrapolated range, two important considerations are made. 1) The neutron and proton channels are mirror channels: i.e. the residual nuclides ^{23}Mg and ^{23}Na are mirror nuclei with nearly identical low-lying structure. Any differences between corresponding n and p channels should be due mainly to Coulomb barrier penetrability and the different Q-values. 2) The only open neutron channels at astrophysical energies are n_0 and n_1 (direct population of the ground and 1st excited states in ^{23}Mg) and that experimental cross section data exists in this energy range [15]. Therefore, we have taken a similar approach as Dayras by using a statistical model calculation to estimate the neutron branching ratio. The difference is that we calculate the ratio $\frac{n_0+n_1}{p_0+p_1}$ and apply this to the experimental data from Ref. [15]. In this way, the resonance structure should be accurately represented. The statistical model should be able to provide a reasonable calculation of this ratio since the primary influences are the Q-values and Coulomb barrier effects as mentioned above, while nuclear structure effects largely cancel out. Indeed, the level of agreement with experimental neutron data is quite remarkable; generally less than 40% deviations for E_{cm}<5.5 MeV [19]. Details of the calculation are provided in Ref. [19] which use the statistical model TALYS (www.talys.eu) with input from the CC calculation of Ref. [13] for the entrance channel spin populations. The agreement with experimental data provides confidence in the extrapolation to lower energies (Fig. 4). An additional improvement is the quantification of the uncertainty which is mainly related to the deviation of the calculation from experimental data [19]. The resulting uncertainty translates to a mere 50% uncertainty in the reaction rate at typical shell-carbon burning temperatures [19]. This is a vast improvement compared to the previous values which have been assumed to be as high as a factor of 10 variation [21].

4 Summary

An accurate knowledge of the low-energy ^{12}C+^{12}C cross section is critical for modeling a number of astrophysical systems including massive stars, type Ia supernovae, and x-ray superbursts. Unfortunately, the excitation function is complicated by resonances whose structure cannot be predicted when extrapolating the measured cross section into the lower astrophysical energy range. As a result, the astrophysical rate is quite uncertain. Recent work at NSL has aimed to reduce the uncertainties associated with these low-energy resonances. The first study, highlighted in Sect. 2, helped establish an upper limit on the ^{12}C+^{12}C fusion rate by examining correlations between the carbon isotope fusion excitation functions. This result has already provided an important constraint for superburst models [27].

The second project from NSL (Sect. 3) was focused on reducing the uncertainty in the astrophysical rate of ^{12}C(^{12}C,n)^{23}Mg. The cross section has been measured deep within the astrophysical energy range. Additionally, an improved extrapolation based on experimental data of the mirror proton channels ^{12}C(^{12}C,p$_{0,1}$) has been provided to estimate the remaining low energies. This result greatly reduces the rate uncertainty as well as provides a quantification of the uncertainty for stellar models, giving important constraints for modeling of heavy element production in massive stars.

Acknowledgements

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